

# **A LARGE-SCALE STUDY ON THE EFFECT OF AMBIENT CONDITIONS ON HYDROGEN RECOMBINER-INDUCED IGNITION**

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## **ABSTRACT**

Hydrogen recombiners (known in the nuclear industry as passive autocatalytic recombiners - PARs), in general, can be utilized for mitigation of hydrogen in controlled areas where there is potential for hydrogen release and ventilation is not practical. Recombiners are widely implemented in the nuclear industry, however there are other applications of recombiners outside the nuclear industry that have not yet been explored practically. The most notable benefit of recombiners over conventional hydrogen mitigation measures is their passive capability, where power or operator actions are not needed for the equipment to remove hydrogen when it is present.

One of most significant concerns regarding the use of hydrogen recombiners in industry is their potential to ignite hydrogen at elevated concentrations (>6 vol.%). The catalyst, heated by the exothermal H<sub>2</sub>-O<sub>2</sub> reaction, is known to be a potential ignition source to cause hydrogen burns. An experimental program utilizing a full-size PAR at the Large-Scale Vented Combustion Test Facility (LSVCTF) has been carried out by Canadian Nuclear Laboratories (CNL) to investigate and understand the behaviour of hydrogen combustion induced by a PAR on a large-scale basis. A number of parameters external to the PAR have been explored including the effect of ambient humidity (steam) and temperature. The various aspects of this investigation will be discussed in this paper and examples of results are provided.

## **1.0 INTRODUCTION**

Accumulation of hydrogen through an accidental release may be difficult to mitigate in certain scenarios (for example, nuclear waste storage tanks or battery rooms, etc.). The difficulty may be due to high costs of ventilation, or due to the location where hydrogen may be released, that does not practically allow the atmosphere to be vented to the environment. Hydrogen recombiners (PARs) can be utilized in such scenarios to mitigate the accumulation of hydrogen and ensure that flammable levels of hydrogen are not reached.

Hydrogen recombiners are most commonly exploited in nuclear power plants to mitigate hydrogen risk in the unlikely event of an accident. Hydrogen can be released in a nuclear accident through various mechanisms, such as oxidation of zirconium alloy reactor components or radiolysis of water. Hydrogen recombiners utilize a catalyst to promote the recombination of hydrogen and oxygen (in air) to produce water vapour and heat, and an open-ended rectangular geometry to promote convective flow (graphical representation shown in Figure 1). In nuclear reactors, PARs are relied upon to limit the hydrogen concentration below the lower flammability limit (LFL – 4 vol.%). However, if the accidental release rate of hydrogen is greater than the total recombination rate of the PARs installed, local hydrogen concentration in containment will increase. At higher hydrogen concentrations (above 6 vol.%), it is possible for the recombiners (PARs) to become an ignition source and initiate a hydrogen burn. Ignition of hydrogen is not desired since the overpressure caused by the hydrogen combustion may adversely affect containment integrity. In general, the overpressures from deflagrations at lower hydrogen concentrations (6 to 8 vol.%) without significant turbulence are tolerable, but overpressures from deflagrations at higher hydrogen concentrations (greater than 8 vol.%) or accelerated flame and detonations are not acceptable [1].

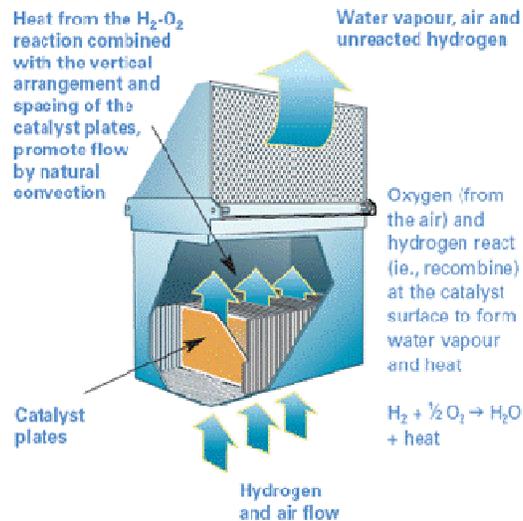


Figure 1. Principle of the PAR operation

The issue of PARs causing a hydrogen ignition reached a critical point in the nuclear industry in 2012. A petition was submitted to the United States Nuclear Regulatory Commission to remove hydrogen recombiners from the Indian Point-2 pressurized water reactor (PWR) due to concerns that a PAR could become an ignition source during an accident [2]. Regardless of the merit behind the petition, it generated international interest on determining the parameters that effect PAR-induced ignition.

Detailed experimental investigations to determine what conditions the hydrogen recombiner will act as an ignition source have not been found in the open literature. Through qualification of the PAR for nuclear reactors, CNL (formerly Atomic Energy of Canada Limited – AECL) has established a database of PAR induced ignition experiments. However, only a small number of test results from the database could be applied to understanding the conditions that could affect the PAR as an ignition source. Thus, a detailed investigation into PAR-induced ignition was completed mainly to identify the conditions (such as, hydrogen concentration, ambient temperature, and humidity) under which a PAR would induce a hydrogen ignition.

The experimental study on the effect of various parameters external to the PAR including the effect of ambient humidity/steam and temperature will be presented in this paper. The different aspects of this investigation will be discussed and examples of results will be provided.

## 2.0 PAR INDUCED IGNITION

Owing to the exothermic reaction between hydrogen and oxygen ( $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$   $\Delta H = -241.81 \text{ kJ/mol}$ ), the PAR catalyst temperature increases with exposure to elevated hydrogen concentrations. Hydrogen deflagration can be initiated at higher hydrogen concentrations (typically above 6 vol.%) due to the resulting catalyst temperatures (above 600 °C).

Hydrogen ignition caused by recombiners can be characterized by regimes of recombiner operation as detailed by Meynet and Bentaib [3]. For instance, at low PAR inlet hydrogen concentration (0 to approximately 6 vol.%), the PAR operates in the catalytic regime (dominated by surface reactions - no ignition); at approximately 6 to 10 vol.% hydrogen at the recombiner inlet, it operates in the transition regime (catalytic and gas phase reactions take place); finally, between 10 to 20 vol.% hydrogen, the PAR operates as an ignition source (gas phase reactions predominate). For this study, the transition regime is of most interest, where the hydrogen ignition is onset. Both gas phase and surface reaction mechanisms produce chain branching radical species (for example,  $\bullet OH$ ), which initiates the hydrogen ignition process. Ignition takes place when the production of radical species is greater than their

destruction (typically brought about by the production of  $\text{HO}_2^\bullet$ ). It is expected that the energetic chain branching radicals exit the PAR and make contact with a rich hydrogen atmosphere (gas phase regime), where the production of radicals is sustainable and causes the hydrogen to ignite.

Based on the theory of PAR-induced hydrogen ignition explained above, the parameters that directly impact when ignition will take place are hydrogen concentration and catalyst temperature. Additionally, ambient temperature and humidity can affect the catalyst temperature and the flammability limit of hydrogen [4], so in theory a relationship exists between ambient temperature and humidity with regard to PAR-induced ignition conditions.

A number of experimental studies have been published on the ignition potential of PARs [5-7]. Analytical methods have been developed in order to predict PAR-induced ignition based on experimental studies that have also been reported [3, 8, 9]. These research efforts have made significant progress toward the understanding of hydrogen ignition initiated by recombiners; however, gaps remain within the experimental and analytical domain. Attempts to close some of the gaps (such as effects of oxygen starvation and ambient conditions) have been made by utilizing the analytical tools by Meynet et al. [8, 9]; however, experimental data is required in order to confirm these results.

### **3.0 EXPERIMENTAL SET-UP**

#### **3.1 Large-Scale Vented Combustion Test Facility (LSVCTF)**

The experiments for the present study were performed in the Large-Scale Vented Combustion Test Facility (LSVCTF) located at CNL's Whiteshell Laboratories (Manitoba, Canada).

The LSVCTF test chamber can be divided into multiple rooms (Figure 2). For the current study, only the front chamber was used (approximately  $60 \text{ m}^3$ ). The end walls and the central vertical partition were covered with rectangular steel plates that were bolted to the wall structures. Some steel plates were removed for the PAR ignition experiments, so the front end wall had a vent opening of  $1.1 \text{ m}^2$ . Four hydraulic mixing fans in the front chamber ensured mixing during gas addition.

A standard recombiner design was used for the PAR-induced ignition study. The PAR housing was installed near the centre of the front chamber using a floor support (inlet  $\sim 1.2 \text{ m}$  above the floor). The recombiner could not be located in the centre due to instrument racks occupying the centre position (see Figure 2 for the general PAR location).

Thirty-one (31) new catalyst elements were installed in the PAR housing for this study. Of the 31 catalyst elements, seven were instrumented with thermocouples. One catalyst element had three thermocouples in a vertical line down the centre of the catalyst element (denoted top, middle and bottom). This element was installed in the centre slot of the PAR.

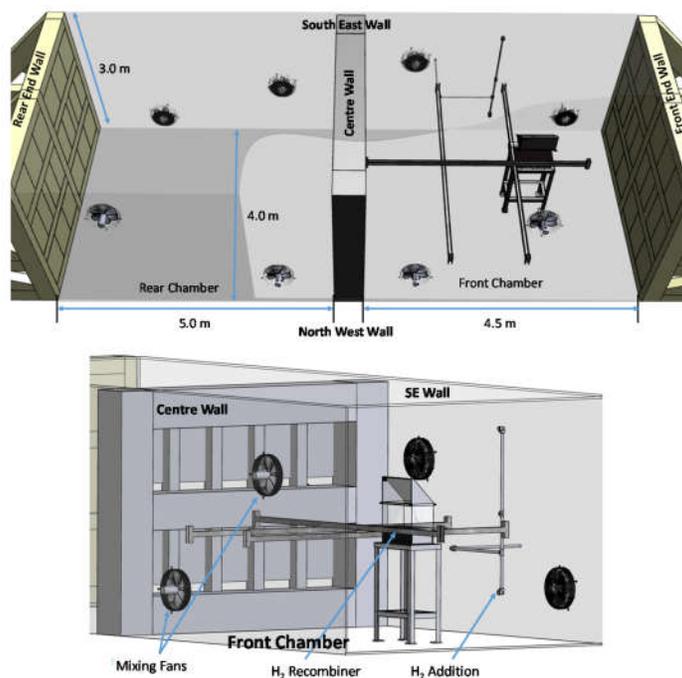


Figure 2. Graphical representation of the LSVCTF

### 3.2 Instrumentation

Gas compositions were measured using an industrial process mass spectrometer at four locations (PAR inlet, PAR outlet, top of the test chamber and middle of the test chamber). At the beginning of the hydrogen addition, all the samples were analysed, but once the desired hydrogen concentration was established, the number of sample locations was reduced from four to one sampling location (PAR inlet), so the sampling rate at the required location was increased. The total uncertainty of the  $H_2$  concentrations measured was within 0.3 vol.% (absolute).

The relative humidity (RH) in the test chamber was measured using a Vaisala HMP 235 RH/temperature probe and a Vaisala HMT 337 RH/temperature probe. After calibration, the maximum uncertainty of the RH probes was 3% RH.

Temperatures were measured at gas sampling locations, catalyst surface, and on the PAR housing using Type K thermocouples. Accuracy in the gas temperatures was measured to be within  $\pm 3.0$  °C. Due to the surface contact of the thermocouple to the catalyst, the accuracy of thermocouples attached to catalyst was estimated to be  $\pm 10$  °C.

The hydrogen deflagration was observed using Gobi 384 and Gobi 640 infrared (IR) cameras. Both IR cameras were calibrated between 300 to 1200 °C, but were used for visualization purposes only.

### 3.3 Experimental Approach

Traditionally, PAR-induced ignition experiments were performed by adding hydrogen to the test chamber with the mixing fans on. At first, hydrogen was added at a high flow rate, then when approaching the desired hydrogen concentration, the flow rate was reduced. Once the desired hydrogen concentration was reached, hydrogen addition was stopped, multiple gas sampling locations were reduced to sample only from the PAR inlet, and the mixing fans were turned off. The infrared (IR) camera was set to record and all data acquisition systems were monitored. If ignition was observed (from monitoring the catalyst temperature or the IR camera), the facility was purged and the test was ended. If ignition did not occur, then the mixing fans were turned on and hydrogen was added

to the test chamber, so the hydrogen concentration was elevated slightly above the previous hydrogen concentration attained. If ignition occurred with the fans on, it typically took place when hydrogen was being added to the facility.

Prior to performing the initial PAR-induced ignition experiments, it was expected that the most difficult component in performing the tests would be to achieve ignition with the mixing fans turned off and maintaining the initial conditions (such as hydrogen concentration, ambient temperature, and humidity). This was of particular concern, since the ideal test sequence was to approach the ignition limit by increasing the hydrogen concentration in more than one step (for example, 7.0 vol.% - no ignition, 7.2 vol.% - no ignition, 7.5 vol.% - ignition achieved). However, it is known that maintaining the humidity and ambient temperature conditions in the facility is difficult after the recombiner begins to operate ( $>1$  vol.%  $H_2$ ), since it outputs water vapour and heat. Additionally, when operating, the recombiner is continually altering the hydrogen concentration in the facility, thus all initial parameters are difficult to control while the PAR is operating. Therefore, a new experimental approach was developed to establish stable initial experimental conditions.

In principle, impeding the operation of the recombiner would reduce the catalyst temperature, and would reduce the rate that the PAR alters the test chamber conditions. A spring-loaded aluminium storm window shutter system was designed and installed on the PAR inlet. A pneumatically-operated cylinder was used to control the position on the shutter (opened or closed - see Figure 3). The shutter system was selected due to its ability to roll up and not interfere with the gas flow at the PAR inlet. The pneumatic cylinder was controlled from the facility remote control building, to allow the LSVCTF operator to open and close the shutter when desired.

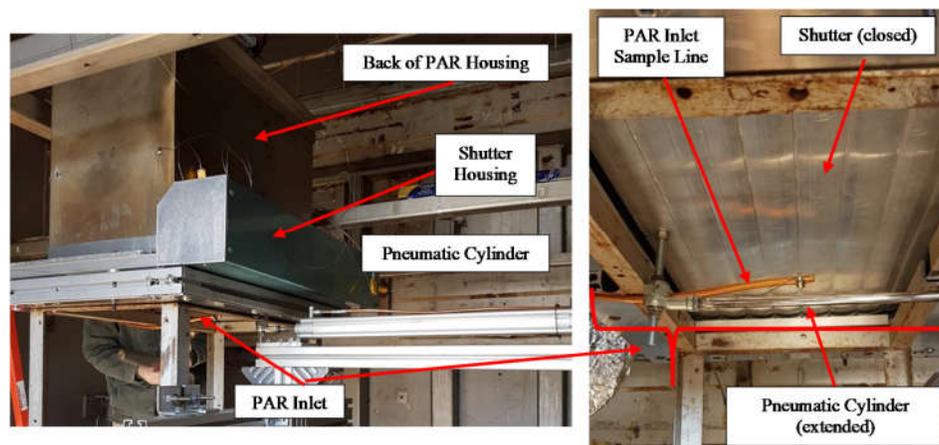


Figure 3. Photographs of the PAR inlet with the PAR shutter system

Once the shutter system was commissioned on the PAR inlet, the experimental procedure was updated to the following process. Prior to each experiment, the vents on the front of the test chamber were covered with aluminium foil to prevent the loss of gases during the experiment and could be easily ruptured under ignition pressure. Mixing fans were turned on to initiate the gas addition phase of the test. Steam (if applicable) was added to the test chamber to achieve the desired humidity level. At first, the hydrogen was added at a high flow rate, then when approaching the desired hydrogen concentration, the flow rate was reduced. Once the desired hydrogen concentration was reached, hydrogen addition was stopped, multiple gas sampling locations were reduced to sample only from the PAR inlet, and the mixing fans were turned off. The infrared (IR) camera (if available) was set to record and the shutter on the PAR inlet was opened to allow full operation of the PAR. All measurement signals were monitored (most importantly the catalyst temperatures) through the data acquisition system.

If ignition was observed (evidenced by a simultaneous sharp increase in catalyst temperature and decrease in hydrogen concentration or flame expansion from the IR camera), the facility was purged and

the test was ended. However, if ignition did not occur after the catalyst temperatures reached a maximum and began to decrease, the process was then repeated, where fans were turned on and more hydrogen was added to the test chamber, etc. After ignition was observed, the IR camera recording was stopped and the facility was purged with fresh air.

#### 4.0 RESULTS

A total of 27 tests were completed to determine the conditions under which the PAR induced a hydrogen ignition. The 27 tests were performed at ambient temperatures ranging from 20 to 75 °C and steam concentrations varying from 0.3 to 28.1 vol.%. In general, the PAR was found to ignite hydrogen with hydrogen concentrations ranging from 7.4 to 9.2 vol.% and catalyst temperatures from 630 to 800 °C.

An example of one of the ignition tests performed, showing the hydrogen concentration and temperature profiles, and humidity and ambient temperature profiles, is provided in Figure 4 and Figure 5, respectively. The two figures illustrate the method of conducting the PAR-induced ignition experiments. In the particular test shown, three attempts were made at a PAR-induced ignition. To begin the experiment steam was added to the test chamber at approximately seven minutes (see Figure 5) with the mixing fans operating (hydrogen concentration, temperature and RH traces are close together). Once 100% RH was achieved, the steam addition was stopped and hydrogen was added to the test chamber. After the peak hydrogen concentration was reached at approximately 8.2 vol.%, the mixing fans were turned off and only the PAR inlet sample line was used. The shutter on the PAR inlet was opened at about 20 minutes and the catalyst temperatures dramatically increased indicating that the PAR was fully operating. The hydrogen concentration decreased and the humidity increased, however no ignition was evident. A second attempt was made with a hydrogen concentration of 8.4 vol.%, a significantly lower RH and slightly higher ambient temperature (an increase of 5 °C). Again, no ignition was found on the second attempt. Finally on the third attempt, with 8.6 vol.% hydrogen, 50 °C and 58% RH, the PAR induced a hydrogen ignition, where a sharp increase in temperature (catalyst, ‘Middle Global’ and ‘Top Global’ measurement locations) and a rapid decrease of hydrogen concentration is shown in Figure 4 and Figure 5.

It should be noted that the experiments discussed here were performed on the same set of catalyst elements. Therefore, the PAR was found to retain its design integrity and behaviour after repeated combustion events.

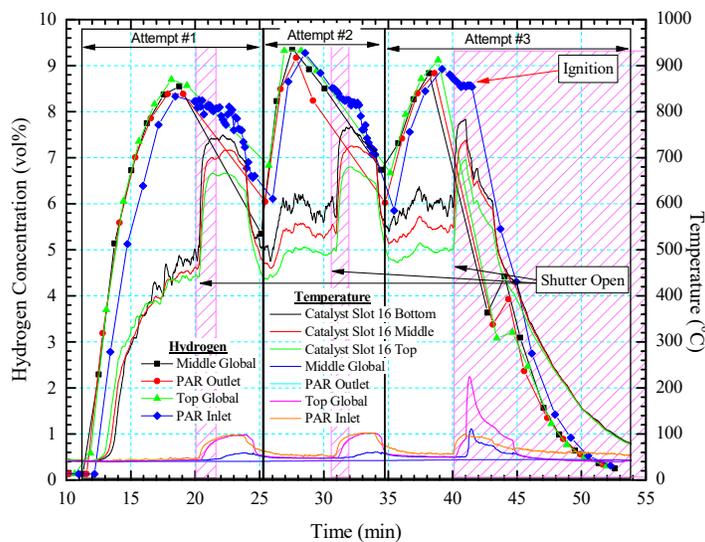


Figure 4. Ambient and catalyst temperature and hydrogen concentration profiles from PAR-induced ignition test PIT034

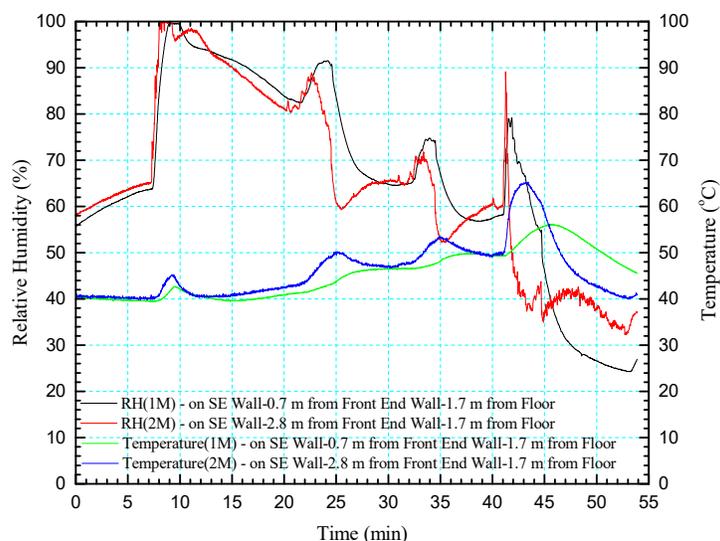


Figure 5. Relative humidity and ambient temperature profiles from test PIT034

#### 4.1 The Effect of Humidity on PAR-Induced Ignition

The PAR-induced ignition tests performed provide data on what conditions the PAR will act as an ignition source; conversely, the results from the tests can also be interpreted to determine the conditions the recombiner does not act as a hydrogen ignition source. Even with the shutter system installed on the recombiner inlet to prevent changes in the atmosphere during hydrogen addition and mixing, the PAR operation did not completely stop. Thus, as illustrated in Figure 4 and Figure 5, the ambient conditions (such as temperature and humidity (steam concentration)) still changed over numerous attempts. It should be noted that the steam concentration taken for the ignition condition is the value recorded prior to the time of ignition. Therefore, each attempt in a given test may be at a significantly different steam concentration. Table 1 provides a summary of the results from the 27 tests grouped by steam concentration.

Table 1. Summary of PAR ignition experiments - grouped by steam concentration range

Steam Concentration Grouping (vol.%)	Bounding PAR-Ignition H <sub>2</sub> Concentration
0 to 2 (low steam)	7.3 to 7.4
3 to 5 (low-medium steam)	8.0 to 8.2
5 to 8.5 (medium steam)	8.2 to 8.3
Approximately 12 (medium-high steam))	7.8 to 8.5
23 to 28 (high steam)	8.6 to 9.0

The data from all 27 experiments was evaluated and the bounding PAR-ignition hydrogen concentrations were determined. The range of hydrogen concentrations that the PAR is expected to ignite hydrogen can be identified from Table 1. From each steam concentration grouping, the attempt with the highest hydrogen concentration where ignition did not occur and the attempt with the lowest hydrogen concentration where ignition did occur can be used to create the bounding range for PAR-ignition. For example, in the low steam (0 to 2 vol.% steam) group, 13 attempts at hydrogen ignition were made, six of which yielded no ignition and the remaining seven all successfully had ignited. The attempt with the highest hydrogen concentration which did not yield an ignition was 7.3 vol.%, while the lowest hydrogen concentration that successfully had ignition was 7.4 vol.%. Thus, these data suggest that ignition will occur between 7.3 and 7.4 vol.% hydrogen. The PAR-induced hydrogen ignition limits was found using the above mentioned analysis method.

Figure 6 provides a plot of the bounding PAR-ignition hydrogen concentrations as a function of the steam concentrations. It demonstrates (following the trend of the bounding hydrogen ignition concentrations) that as the steam concentration increases, the limit for PAR-induced ignition also increases marginally. Based on the trend visible in Figure 6, extrapolating beyond 30 vol.% steam, the minimum PAR inlet hydrogen concentration required to produce an ignition would not increase much beyond 9.0 vol.%.

It is noticeable that the range of hydrogen concentrations that the PAR is expected to ignite hydrogen differs in each steam concentration grouping (for example, low steam concentration has a range of 0.2 vol.% and high steam concentration has a range of 0.5 vol.%). This is due to the number of successful tests that were performed in each steam concentration grouping. The medium-high and high steam concentrations had the fewest tests, therefore, a more defined hydrogen concentration range was not developed.

The relationship found between humidity/steam concentration and the PAR-induced ignition hydrogen concentration can be due to the steam introducing heat transfer dynamics that have a quenching effect to the chain branching radical species that causes the hydrogen to ignite (that is, increased presence of a third body that aids the production of  $\text{HO}_2\cdot$ , which breaks the chain reactions) [10]. As a result, higher hydrogen concentrations are needed to overcome the quenching caused by the steam. This theory can also be explained through the catalyst temperature. Higher catalyst temperatures can be expected to produce more chain branching radical species. Under higher steam concentrations, higher hydrogen concentrations and higher catalyst temperatures are needed to induce a hydrogen ignition. This phenomena can be explained by the fact that the steam has a negative effect on the radical species being produced, therefore, ignition occurs in conditions where a higher rate of radical species production exists.

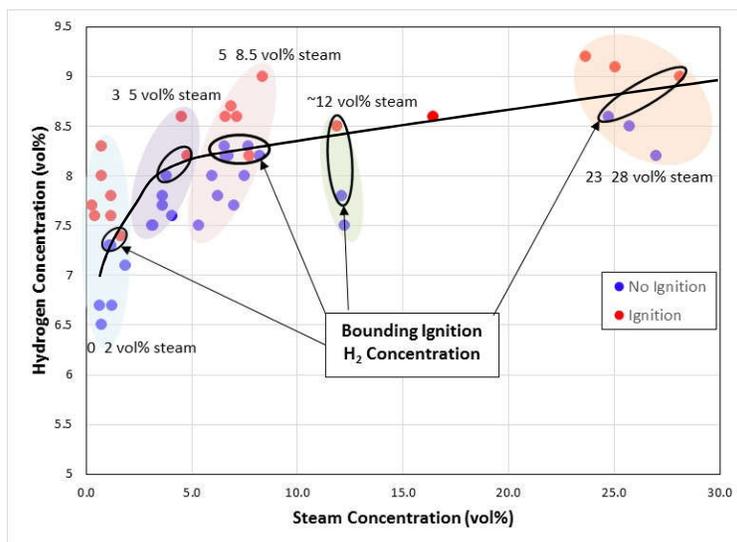


Figure 6. PAR-induced ignition attempts comparing steam and hydrogen concentrations

#### 4.2 The Effect of Ambient Temperature on PAR-Induced Ignition

The steam concentration and ambient temperature of the test chamber were controlled independently in order to allow the analysis of each of their effects on PAR-induced ignition. To investigate the effect of temperature independent of the steam concentration, the data was analysed utilizing a similar method as the analysis on the effect of steam concentration, in which the attempts that yielded ignition and no ignition were used. Also, similar to the effect of steam analysis, the tests (ignition attempts) were organized by steam concentration groups, then further assembled into sub-groups based on temperatures 30 to 38, 38 to 49, 50 to 59, and 60 to 65 °C.

Within the sub-groups, the attempts were organized by ascending hydrogen concentration. Steam concentration groups in the medium-high and high range were not included in the analysis because the tests at these humidity ranges were only performed at one range of temperatures.

Similar to the analysis for the effect of humidity, the ambient temperature data can be analysed to determine the range of hydrogen concentrations in which the PAR is expected to ignite hydrogen by selecting the attempt with the highest hydrogen concentration where ignition did not occur and selecting the attempt with the lowest hydrogen concentration where ignition did occur. Table 2 provides a summary of the analysis at each ambient temperature sub-group within each steam concentration group.

Table 2. Summary of PAR ignition experiments - grouped by steam concentration and temperature ranges

Steam Concentration Grouping (vol.%)	Ambient Temperature Grouping (°C)	Bounding PAR-Ignition H <sub>2</sub> Concentration
0 to 2 (low steam)	30 to 38	7.1 to 7.6
0 to 2 (low steam)	38 to 49	7.3 to 7.4
0 to 2 (low steam)	50 to 59	7.3 to 7.6
3 to 5 (low-medium steam)	38 to 49	8.0 to 8.2
3 to 5 (low-medium steam)	50 to 59	7.8 to 8.6
5 to 8.5 (medium steam)	38 to 49	8.2 to 8.3
5 to 8.5 (medium steam)	50 to 59	8.3 to 8.6
5 to 8.5 (medium steam)	60 to 65	8.2 to 9.0

As found in Table 2 and shown in Figure 7, within each steam concentration group, the hydrogen concentration needed for PAR-induced ignition is not clearly affected by ambient temperature. There may be a slight trend suggesting that the hydrogen concentration with respect to ambient temperature is increasing, but this is inconclusive. The hydrogen concentration ranges overlap by quite a large value in some cases.

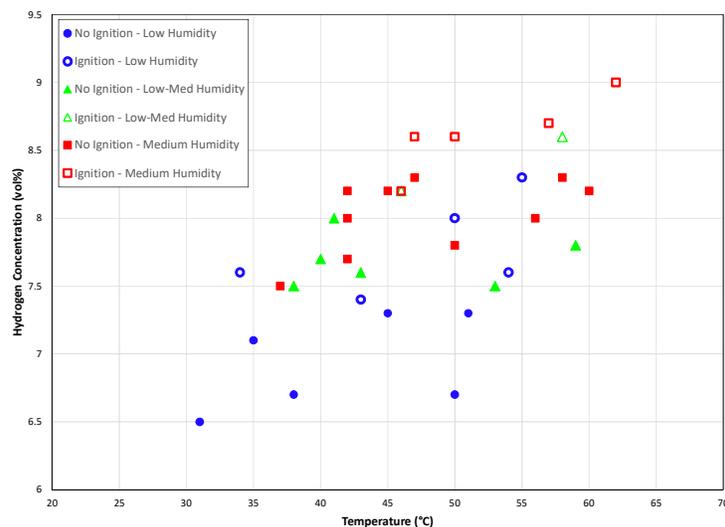


Figure 7. PAR-induced ignition attempts comparing ambient temperature and hydrogen concentrations

There was no expected effect of ambient temperature within the range of this study covered (25 to 65 °C) on PAR-induced ignition.

Reviewing literature on hydrogen ignition by a hot surface indicates that, in the temperature range between 25 to 125 °C, the chain branching radicals responsible for ignition are not formed at a significantly higher rate to influence ignition behaviour [10]. Further, the catalyst temperature is not affected by the ambient temperature in the range of 25 to 65 °C and the convective flow has only a minor effect due to the ambient temperature varied in the same range. From the study reported by Meynet et al. [8], the PAR-induced ignition hydrogen concentration is expected to decrease marginally with increased ambient temperature. Although no discernible trend was found from the present study, it is possible that the bounding ignition hydrogen concentrations have a range too large to identify a difference between temperature groupings.

The grouping above also furthers the point of the effect of humidity on PAR-induced ignition. Based on the data analysis above, when the common ambient temperature groups are selected, it is evident that as the steam concentration increases, the hydrogen concentration required for PAR ignition also increases.

### 4.3 Relationship between Catalyst Temperature and Hydrogen Concentration

It was mentioned above that PAR-induced ignition is dependent on both the hydrogen concentration and the catalyst temperature. However, in the analysis of the effect of humidity and ambient temperature, hydrogen concentration was the main focus due to the dependence of catalyst temperature on hydrogen concentration. Figure 8 provides a representation of the maximum catalyst temperature versus the PAR inlet hydrogen concentration for all the PAR-induced ignition attempts. The data in Figure 8 suggests a relationship that as the hydrogen concentration increases, the maximum catalyst temperature also increases somewhat proportionally. Although the data is quite scattered, Figure 8 also provides some indication that as the ambient humidity increases, the PAR-induced ignition hydrogen concentration and catalyst temperature increases.

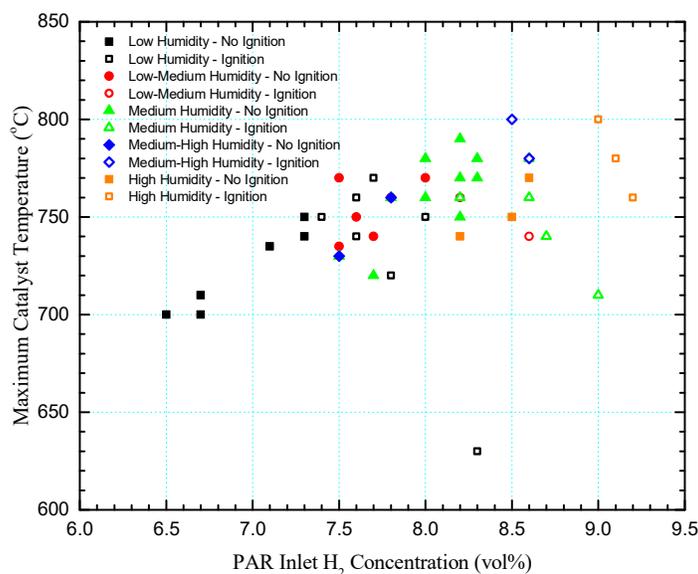


Figure 8. PAR-induced ignition attempts comparing catalyst temperatures and hydrogen concentrations

In general, in the absence of contaminants or catalyst poisons, the maximum catalyst temperature is expected to increase proportionally with hydrogen concentration, where at 7.0 vol.% hydrogen the catalyst elements are about 720 °C, at 8.0 vol.% hydrogen the catalyst elements are about 750 °C, and finally at about 8.5 vol.% hydrogen the catalyst elements are about 770 °C. However, in some test cases, the relationship between hydrogen concentration and maximum catalyst temperature falls well outside this range.

For example, in one particular test, hydrogen ignition occurred on the first attempt, with a reasonably high hydrogen concentration (8.3 vol.%) in the low humidity range, but the maximum catalyst temperature was by far the lowest of all the PAR ignition tests (630 °C). The cause of this is likely because the shutter was opened too late in the test. When the shutter was closed, the hydrogen concentration in contact with the catalyst was lower than measured at the PAR inlet (outside of the recombiner). After the shutter was opened, the hydrogen concentration was well beyond the ignition point for the test conditions (expected to occur around 7.3 to 7.4 vol.% hydrogen). The use of the shutter allows for hydrogen concentrations to be reached that are well beyond the PAR-induced ignition range, with 8.3 vol.% hydrogen, but there is increased uncertainty in the PAR ignition threshold if ignition occurs on the first attempt. Without the shutter system on the recombiner inlet, ignition may have occurred with the mixing fans in operation before 8.3 vol.% hydrogen could be reached.

#### 4.4 Summary of PAR-Induced Ignition Results

The results from all the PAR-induced ignition experiments performed at CNL to date with well-mixed, quiescent conditions have been added to the Shapiro diagram in Figure 9. The Shapiro diagram mapping the PAR-induced ignition threshold against the hydrogen flammability and detonation limits has been reproduced from Reference [11]. It is evident from the diagram that the limits have been studied in detail up to 30 vol.% steam and that the results agree well with the historical PAR ignition tests.

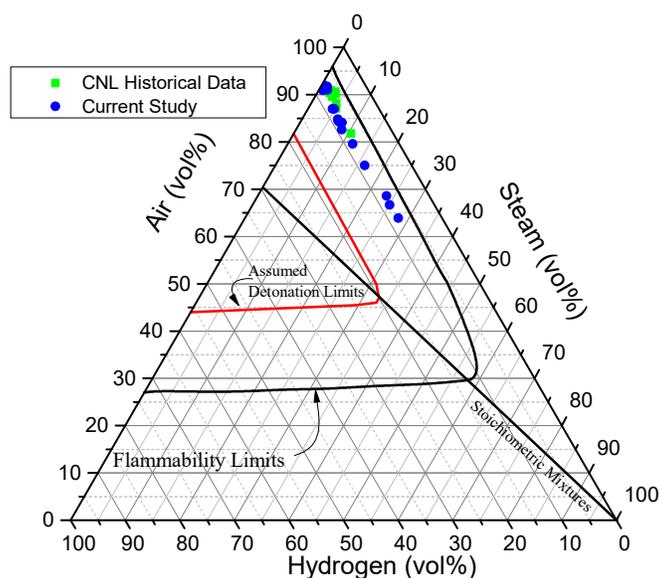


Figure 9. PAR-Induced hydrogen ignition threshold diagram (Shapiro Diagram [11]) at approximately 100 kPa(abs) and 25 to 65 °C

## 5.0 CONCLUSIONS

Two main conclusions can be drawn from the PAR-induced ignition experiments performed under well-mixed, quiescent conditions:

1. A trend was found between humidity (steam concentration) and the PAR-induced ignition hydrogen concentration. Increasing the humidity from dry conditions to 28 vol.% steam resulted in a hydrogen ignition concentration increase from approximately 7.5 to 9.0 vol.%. Based on the trend found, the PAR inlet hydrogen concentration required to induce a hydrogen ignition in conditions exceeding 30 vol.% steam is not expected to increase much beyond 9.0 vol.%.
2. Ambient temperature does not have a significant effect on the hydrogen concentration required for the PAR to induce an ignition within the range covered in this study (25 to 65 °C). The test results are

quite scattered and no trend is evident. This may be explained since the PAR operation only has a minor dependence and ignition behaviour has no significant dependence on ambient temperature up to 65 °C.

All the PAR-induced ignition tests performed to date have been added to a Shapiro diagram in mapping the PAR-induced ignition tests threshold against the hydrogen flammability and detonation limits. Based on the Shapiro diagram, the experimental results from this study agree well with the reported literature [3, 6, 8, 9]. Most importantly, the PAR retains its design integrity and behaviour after repeated combustion events (from testing).

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